

Development of terahertz gyrotrons and their application to CTS on LHD

T Saito¹, T Notake², Y Tatematsu¹, A Fujii¹, S Ogasawara¹, La Agus¹,
T Idehara¹, S Kubo³, T Shimozuma³, K Tanaka³, M Nishiura³, K Kawahata³,
V N Manuilov⁴

¹ FIR FU, University of Fukui, 3-9-1 Bunkyo, Fukui-shi, 910-8507, Japan

² Riken, Sendai, Japan

³ National Institute for Fusion Science, 322-6 Oroshi-cho, Toki-shi, 509-5292, Japan

⁴ Nizhny Novgorod State University, Nizhny Novgorod, 603600, Russia

saitot@fir.u-fukui.ac.jp

Abstract. Development of a high-power, sub terahertz pulse gyrotron has started in FIR FU for application to CTS on LHD. A new electron gun was designed to produce a laminar electron beam with a good quality. Second harmonic TE_{6,5} and TE_{8,5} modes were selected as oscillation modes well isolated from other competing modes. Single mode oscillation has been confirmed for both TE_{6,5} and TE_{8,5} modes. The maximum power is larger than 50 kW for TE_{6,5} mode (0.349 THz) and about 40 kW for TE_{8,5} mode (0.390 THz). These powers are new records of second harmonic gyrotron in this frequency range. Feasibility study of CTS with a 0.4 THz pulse gyrotron from a high density plasma in LHD was carried out. The CTS condition is satisfied for a wide operation regime and scattering angles large enough for good spatial resolution. Ray tracing calculation shows that the launched scattered beams are propagated almost straight. CTS spectra calculated with a newly developed code indicates that a large signal to noise ratio can be obtained against ECE for use of a 100 kW gyrotron.

1. Introduction

Recently, application of high frequency gyrotrons as high power sources in the sub terahertz region has been spreading to various fields. Among those, development of a sub terahertz high power pulse gyrotron as a power source of collective Thomson scattering (CTS) diagnostics on high density plasmas is a challenging task. We have started this study for CTS on the large helical device (LHD).

For a power source of CTS, fusion grade gyrotrons with frequencies from tens of GHz to 140 GHz are considered and experiments with these gyrotrons have started [1]. However, electromagnetic waves with these frequencies suffer from a strong plasma dispersion effect when they are applied to a high density plasma. Moreover, high level background electron cyclotron emission (ECE) is a large noise source. Use of a sub-terahertz gyrotron will resolve these problems. In advance of gyrotron development, the condition of CTS was examined. Figure 1 shows the region in which the CTS condition $\alpha = 1/k\lambda_D > 1$ holds in space of scattering angle and wavelength of the probe beam [2]. When we set the gyrotron frequency at 0.4 THz, the CTS condition is satisfied for a sufficiently large scattering angle over a wide operation range of LHD; N_e up to several times 10^{20} m^{-3} and T_e in the range of several keV. This frequency is larger than the fifth harmonic electron cyclotron frequency at

2.75 T and background ECE as well as plasma dispersion effects can be substantially reduced. On the other hand, difficulty of gyrotron development increases with frequency and CTS power decreases with frequency. Therefore, 0.4 THz is an appropriate choice. The target power is set to be 100 kW at the moment.

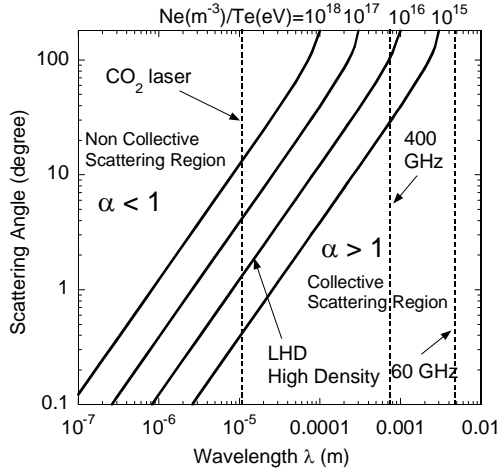


Figure 1. Collective scattering region is shown for the wavelength of the power source. Parameter is the ratio of the electron density in m^{-3} to the electron temperature in eV.

Research center for development of far-infrared region, University of Fukui (FIR FU) is developing high frequency gyrotrons up to 1 THz [3]. We have started the challenging task of development of a high-power, sub terahertz pulse gyrotron [2, 4]. In this paper we report the performance of the developed pulse gyrotron. Preliminary feasibility study of CTS on LHD with a 0.4 THz pulse gyrotron is also presented.

2. Development of sub terahertz high power pulse gyrotron

The design of the developed gyrotron consists of three aspects. Use of a newly designed electron gun is the first aspect [5]. This electron gun generates a laminar electron beam with a good quality for the beam voltage V_k of 60 kV, the beam current I_b of 7 A and those of 70 kV, 10 A. The second aspect is selection of the oscillation modes that are well isolated from other competing modes. In particular, isolation from fundamental modes is very important for a second harmonic mode to oscillate as a single mode. We have searched many candidate modes and finally selected two modes $\text{TE}_{6,5}$ and $\text{TE}_{8,5}$. The electron beam optics is the third aspect and it is closely connected with the mode selection because the electron beam radius R_b at the cavity should coincide with the peak radius of the coupling coefficient between the electron beam and the wave field. In this design the second peak of the coupling coefficient is used owing to limitation of the electron beam optics. The cavity dimensions are 2.99 mm in radius and 12 mm in length of the straight section [6]. The resonance frequency is 350 GHz for the $\text{TE}_{6,5}$ mode and 392 GHz for the $\text{TE}_{8,5}$ mode, respectively. A theoretical model [7] predicts more than 30% perpendicular efficiency even for the second peak coupling and the oscillation power of about 80 kW for the pitch factor of the electron beam of 1.3.

Figure 2 (a) shows oscillation intensities as functions of the magnetic field at the cavity with V_k as a parameter. The beam current is fixed at 5 A. Figure 2 (b) indicates oscillation intensities measured through a high pass filter with the cutoff frequency of 303 GHz. Then, peaks in figure 2 (b) indicate second harmonic oscillation. The modes were identified as the $\text{TE}_{6,5}$ and $\text{TE}_{8,5}$ modes respectively from frequency measurement with a Fabry-Perot interferometer. In the lower field side to the $\text{TE}_{8,5}$ mode peak, the $\text{TE}_{17,2}$ mode may oscillate. Single mode oscillation was checked for each mode by using the Fabry-Perot interferometer without the high pass filter. Single mode oscillation of the two modes was confirmed for operation up to $V_k = 60$ kV and $I_b = 11$ A.

Oscillation power was measured with a water load installed just outside of the vacuum window. The present gyrotron has no internal mode convertor and the oscillation power is transmitted to the

vacuum window through a straight section with an up taper. The normal pulse width for power measurement is 1 μ s and the repetition frequency is 10 Hz. Beam current dependence of the output power of the TE_{6,5} and TE_{8,5} modes were measured. The beam voltage was set at around 57 kV. Since the oscillation power of each mode depends on R_b , the gun coil current was adjusted at each value of I_b . Single mode oscillation was confirmed for each data point. The output power increases with I_b although it rather saturates for I_b larger than 8 A. The maximum power so far obtained is larger than 50 kW for TE_{6,5} mode (0.349 THz) and about 40 kW for TE_{8,5} mode (0.390 THz) [8]. The measured values were corrected considering the transmission coefficients of the vacuum window and the water loads. According to the reported power of second harmonic gyrotrons [9], these values are new records in this frequency range.

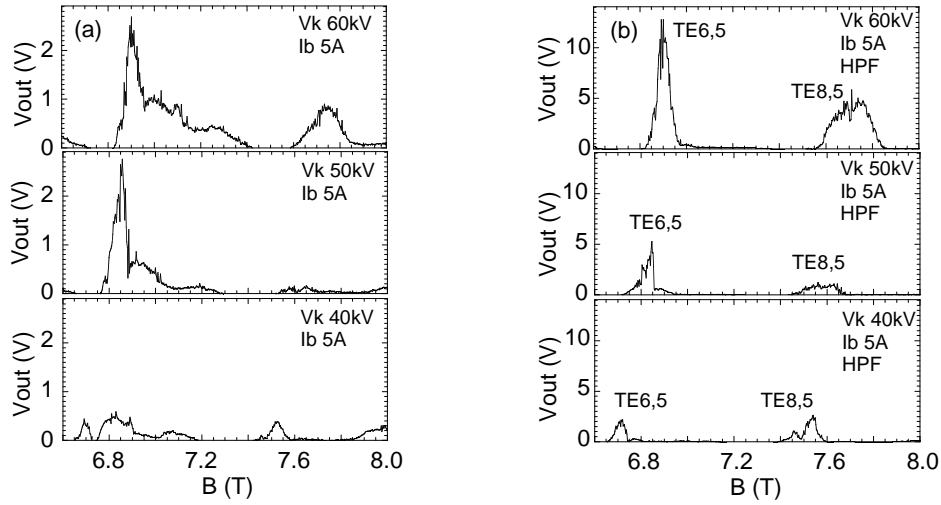


Figure 2. Oscillation intensities are plotted as function of the magnetic field at the cavity with the beam voltage as a parameter. (a) Oscillation intensities were measured at an open end of a waveguide connected to the output window of the gyrotron. (b) A high pass filter with the cutoff frequency of 303 GHz was inserted in between the waveguide end and the detector.

The experimentally obtained maximum total efficiency is 14 % for the TE_{6,5} mode at I_b of 5 A. This value is lower than that expected from calculation with the theoretical model. Moreover, the efficiency further decreases for larger value of I_b . One possibility of the low efficiency is degradation of the quality of the electron beam. Indeed, V_k of 60 kV is rather low for large beam current. Improvement of the beam quality needs higher value of V_k . However, the available voltage is limited at about 60 kV at the moment. We have designed and fabricated a new gyrotron aiming at 100 kW around 0.4 THz with second harmonic oscillation by further improvement of the operating mode and the cavity design. Experiment of this gyrotron has just started. Efforts for higher cathode voltage operation will be done.

3. Feasibility study of collective Thomson scattering on LHD

Two available ports on the LHD vacuum vessel are tentatively chosen for injection and receiving antennas. For this choice, scattering angle θ_s is 104 degrees, which is large enough to obtain high spatial resolution. Beam radius is calculated assuming a Gaussian beam. When the beam radius is focused to $w_0 = 1$ cm at the scattering point, the radius w_1 at the injection port is 5 cm for 0.4 THz. This value is small enough that the antenna can be installed without difficulty.

Next, ray tracing calculations are carried out. A probe beam with frequency of 0.4 THz propagates through a plasma of the peak electron density of 10^{20} m⁻³ and reaches the center of plasma without refraction. Waves scattered from different points along the incident beam also reach the receiving antenna port straight.

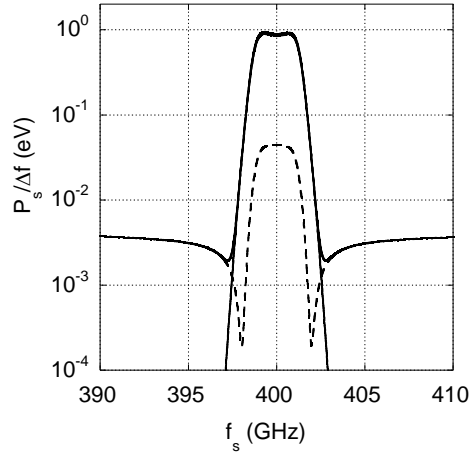


Figure 3. Scattering power spectrum in unit band frequency for $T_e = T_i = 2$ keV, $N_e = 10^{20} \text{ m}^{-3}$. Solid and dashed lines indicate power spectra due to motions of electrons collective and non collective with ions, respectively.

Scattering power spectrum observed at the receiving antenna is evaluated as [10]

$$P_s = P_{in} N_e r_e^2 \Gamma S \Delta f \frac{\lambda_i^2}{\sqrt{\pi} w_0 \sin \theta_s}$$

where P_{in} is the gyrotron power, N_e is the electron density, r_e is the classical electron radius, λ_i is the wavelength of the incident wave, Δf is the detection band width, Γ is the geometrical factor [11] and S is the scattering form factor. An example of power spectrum is shown in figure 3, where $P_{in} = 100$ kW, $N_e = 10^{20} \text{ m}^{-3}$ and $w_0 = 1$ cm are assumed. Solid and dashed lines plot the power spectra stemming from electron motion collective with ions and thermal electron motion, respectively. Collective scattering is dominant and the spectrum of P_s gives us ion information. The calculated power per unit frequency band is about 1.0 eV. The background ECE level calculated with a radiation transfer code is less than 0.1 eV for the peak electron temperature of 2 keV [4]. With the pulse width of 100 μs and 100 GHz detection band width, a signal to noise ratio of the order of 100 is expected for the 2.75 T standard operation of LHD.

Thus, 0.4 THz, 100 kW gyrotron is one of promising candidates of power source for CTS from high density plasma in LHD. However, the necessary power should be determined from the total sensitivity of the CTS diagnostic system.

References

- [1] Bindslev H et al., 2006 *Phys. Rev. Lett.* **97** 205005
- [2] Notake T et al., 2008 *Rev. Sci. Instrum.* **79** 10E732
- [3] Bratman V et al., 2009 *IEEE Trans. Plasma Sci.* **37** 36
- [4] Saito T et al., 2008 *Conference Digest of IRMMW and THz*, W5D28
- [5] Manuilov V N et al., 2008 *Int. J. Infrared and Milli. Waves* **27** 1103
- [6] Notake T et al., 2009 *Plasma and Fusion Res.* **4** 011
- [7] Danly B G and Temkin R J 1985 *Phys. of Fluids* **29** 561
- [8] Notake T et al., submitted to *Phys. Rev. Lett.*
- [9] Thumm M 2008 *Wissenschaftliche Berichte FZKA7392*, Research report of Research Center, Karlsruhe Universit
- [10] Sheffield J 1975 *Plasma scattering of electromagnetic radiation* (Academic Press)
- [11] Bretz N 1987 *J. Plasma Phys.* **38** 79